An Ecological View of Smart Home Technologies

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Abstract. In this paper we propose an ecological view in which a smart home is seen as an interconnected collection of smart objects that work together to provide services to inhabitants. We review home technologies in a historical context in which the home is a personal habitat that provides services to inhabitants, and draw lessons from the profusion of new services that were made possible by the introduction of electricity in the home during the 20th century. We examine possible metaphors for smart homes, including the smart home as an inside-out autonomous robot, and the smart home as an ecosystem of smart objects providing services. We propose a taxonomy for smart home services and discuss examples for each class of service. We conclude with a discussion of required system qualities and potential show-stoppers.

Keywords: Smart Objects · Smart Home · Ecological View · Domotics · Intelligent home services · Human Computer Interaction · Ambient Intelligence

1 Introduction

Continued advances in information and communication technologies, coupled with progress in machine learning, sensors, actuators and human computer interaction make it increasingly easy to embed technologies for perception, action, communication and interaction in ordinary human objects. The result is an enabling technology for smart objects and smart environments with the potential to provide revolutionary new services. In this paper we discuss how this technology can be used to create new forms of intelligent services for the home.

We begin by discussing historical barriers to Home Automation, and propose an alternative ecological view of the home as a personal habitat that provides services such as personal protection and shelter from the elements. We examine the profound rupture in the nature of services that resulted from the introduction of electricity in the home at the beginning of the 20th century and draw lessons from the adoption of different forms of electric appliances. We then examine the nature of services that are made possible by the introduction of ambient intelligence in the home.

We propose a taxonomy for smart home services in terms of tools, housekeepers, advisors, and media. For each class, we explore forms of services for different functional areas of the home. We conclude by discussing required system qualities and potential show-stoppers. We argue that establishing proper legal and ethical foundations may be as important as technological research to the long-term acceptance of smart home technologies.

2 Domotics as Home Automation

Much of the early work in smart home technologies has been directed towards automating common tasks such as cleaning, environmental control and energy consumption. More recently, we have seen a big push in the area of health monitoring, particularly for the area of providing autonomy for healthy aging. In most cases, work has been primarily directed towards automating established processes rather than providing a new perspective for how smart technologies can affect the organization of the home.

For many years, smart home technologies were considered to be part of the field of home automation, sometimes referred to as Domotics [1]. The dominant approach was to automate regulation of Heating, Ventilation and Air Conditioning (HVAC) equipment, control of energy consuming appliances such as water heaters, control of lighting, and automatic control of shutters and awnings. Intelligence was provided by analog timers, sensors and finite state machines wired into the home electrical system. Communication signals were based on cables, or in some cases, communication over power lines (CPL). Configuration required a certified electrician. While the high cost of installation was a barrier to such technologies, the biggest obstacle was lack of user control. Programming the behavior of home automation systems based on timers and finite state machines required intervention by a certified technician who generally had little or no understanding of the preferences of inhabitants. Such systems quickly earned a reputation for inappropriate, almost comical behavior.

The arrival of personal computers and wireless communications provided the potential for a technological rupture in home automation. In theory, it became possible to provide home-owners with a computer based "control panel" running on a personal computer, providing information and control of environmental conditions throughout the home. However, to date there has been little penetration of such technology in the home. Frequently cited reasons for this lack of success include

1) The proliferation of closed proprietary standards and protocols,
2) The high cost of installation of sensors and actuators,
3) Dependence on technologies that evolve on time scales that are very different than buildings,
4) Incomprehension of the technology and its use by both architects and classically trained electricians.

In addition to these obvious reasons, a more subtle obstacle also exists. Simply replacing analog timers and finite state automata with centralized digital controls provides only marginal improvements in quality of life. The real gains in quality of life require rethinking the role of intelligent systems in terms of the ecology of the home.

3 The Ecology of the Smart Home

Ecology is the scientific field that deals with the relationships between groups of living things and their environments [2]. An ecological approach is increasingly important to scientific domains such as Biology, Anthropology, Sociology, Economics, Psychology and the Environmental Sciences. Human Ecology, in particular, is the study of the relations between humans and their natural, social, and artificial environments [3]. Human ecology has a fragmented academic history with publications dating back to the mid 19^{th} century, and developments spread throughout a range of disciplines. For example, the term "human ecology" was used in 1907 in a study on the effects of sanitation [4] in terms of the interaction between city sanitation services and domestic hygiene. An ecological approach provides important insights into smart home technologies.

To understand the ecology of the smart home, we need to examine the relation between the habitat and inhabitants. A habitat is the place or environment where a plant or animal normally lives and grows [5]. The term is also used to refer to artificial human environments where people can survive under inhospitable conditions such as on other planets or under the sea. An inhabitant is any plant or animal that lives in a habitat. In this paper we will refer to persons who regularly inhabit a home as inhabitants.

Habitats provide services to inhabitants [6]. For natural habitats, such services can range from providing shelter and security to providing food, water, facilitating biodiversity. We propose to examine the smart home as an ecosystem of smart objects that can individually or collectively provide services to inhabitants. Examining the home as a provider of services reveals a multitude of interesting and attainable possibilities for smart homes, most of which are natural extensions of the historical role of the home. This ecological notion of service should not be confused with Service Oriented Computing.

3.1 A Smart Home is not a HaaS

It would be tempting to write that we are proposing the concept of "Home as a Service" (HaaS), however this would be both inaccurate and misleading. In the technical area of "Service oriented computing", a service is defined as a "logical representation of a repeatable activity that has a specified outcome". Services obey a contract. Software services are self-contained, may be composed of other services, and operate as a "black box" to consumers [7].

The notion of service used in ecology is much closer to the natural language notion of service as "an activity or process that provides something of value". In particular, we are concerned with intelligent services that provide value to inhabitants. In this sense, smart home services cannot be constrained by a contract and may not comply with the accepted definition of a "software service". So, while these definitions may have some overlap, the notion that we are proposing may not be recognizable to the scientific community of service oriented computing, and the concepts and techniques required are not necessarily relevant to that domain.

3.2 Traditional Home Services

From prehistoric times, humans have depended on a home as a personal habitat. Prehistoric homes provided protection of persons and possessions, both from nature and from other species. Homes provide heat and shelter in cold climates, allowing the human species to migrate over much of the planet, with the home providing shelter and protection of possessions, as well as a protected place for grooming, cooking, eating and sleeping. In more modern times, the home has provided light at night through use of tallow lamps and candles followed by gas lamps and electric lighting. [8].

In the late 19th century, the introduction of electricity in the home provoked a rupture in the nature of services that the home could provide. The arrival of electric distribution networks (1883) made possible electric light and electric heat in the home. These were soon followed by vacuum cleaners (1908), the electric iron (1909), clothes washing machines (1910), air conditioners (1911), the refrigerator (1913), electric toasters and hot-plates (1919), home radio (1920), the dishwasher (1922), electric ovens (1930), television (1948), electric can openers (1956), microwave ovens (1967), and the Home Computer (1977). Each of these appliances augmented the services provided to inhabitants by the home.

Bowden et al [9] examine the penetration of durable household appliances in the US and UK during the early 20th century, modeling the diffusion of technologies as a logistics "S" curve. They examine a number of technologies that were introduced to households following the widespread introduction of electricity and rank these based on the number of years between adoption by 20% and 75% of all households. They observe differences in adoption rates for two distinct classes of appliances, referred to as time-saving appliances and time-using appliances.

Time-saving appliances, such as electric irons, vacuum cleaners and washing machines increase the quantity of discretionary time of inhabitants, typically by automating or improving the efficiency of common household tasks. Time-using appliances, such as TV, Radio and the Video Cassette Recorder bring a new function to the home, at the cost of a commitment of discretionary time. Bowden et al show that, contrary to intuition, time-using appliances are typically adopted more rapidly than time-saving appliances. They argue that this is because modern households already have sufficient disposable time and are more interested in improving quality than increasing quantity. One exception is the telephone, whose 75% penetration required 67 years, despite its evolution from a time-saving appliance to a time-using appliance, a phenomena explored in great detail in [10].

The take home message is that inhabitants are more likely to adopt smart objects and smart home services that improve quality of life, rather than increase available leisure time. This argument is reinforced by the observation that many supposedly time-saving appliances such as washing machines and vacuum cleaners have not actually reduced the time spent on chores. Rather they are commonly used to improve hygiene by increasing the frequency of cleaning. The message for smart home technologies is clear. Automating existing processes is not the most effective approach. Smart home technologies that improve quality of life are likely to be adopted much faster than technologies that seek to save time.

3.3 The Smart Home as an Inside-Out Autonomous Robot

We propose to rethink the changes to the role of the home made possible by technologies for ambient intelligence. One obvious approach would be to see the home, itself, as an inside-out intelligent autonomous robot. Just as with autonomous robots, the first task for an intelligent autonomous home would be to observe and protect its own integrity. In biological systems, integrity is maintained by autonomic processes. A primary function for such processes is to maintain homeostasis [11]. For the smart home, homeostasis requires regulating internal environmental conditions, as well as maintaining stable supplies of energy, liquids and consumables. In this sense, starting with regulation of environmental comfort and smart energy are reasonable first steps toward the smart home. The inside-out autonomous robot analogy suggests a number of other fundamental services that are quite attainable with current technology, including maintaining integrity of the infrastructure of the home and its appliances, evacuation of waste, cleaning and management of consumable supplies and fluids.

Autonomy and homeostasis suggest that the environmental conditions and state (opening and closing of windows and doors) of each room in the house should be instrumented to give a better understanding of comfort. Monitoring the energy used by individual appliances and rooms can provide a wealth of information to allow consumers to understand their consumption of energy in order to operate as informed participants in the smart grid. We call this “making energy visible”, and a variety of products and services are currently under development in this area. Similar efforts are possible concerning consumption of water and production of waste-water and sewage, particularly in drought stricken regions. Homeostasis also suggests that the smart home participate in managing the integrity of home appliances, as well as the immediate environment such as lawn and gardens. These are potential areas of rapid progress for the near future.

Similar ideas can be applied to management of cleaning and detection and removal of recyclable trash and organic waste. It should be relatively easy to build sensors that detect cleaning activities for floors, surfaces, windows, walls, furniture and appliances, to provide a summary of the current state of each surface, and indicate when surfaces require cleaning. An objective record of cleaning activities can help with planning for both manual and automatic cleaning, particularly in areas where hygiene is important such as kitchens and bathrooms. Similar information can be collected about the state of trash and garbage.

Beyond simple hygiene, homeostasis also suggests managing logistics for consumables. Maintaining inventory of food and cleaning stocks in the kitchen can help avoid cluttering storage areas and refrigerators with long expired foodstuffs and inedible left-overs, and provide automated shopping lists. Current technologies can be used to equip kitchen cabinets, refrigerators and drawers with low-cost image sensors. Computer vision techniques can be used to keep a record of current inventory including when each item was placed or removed. From this, it is relatively easy to inform users about where utensils can be found, and which foods should or should not be consumed.

This idea can be extended from the kitchen to all storage areas of the home. Closets, pantries, cabinets and dressers can be augmented with visual sensors for contents to provide a record of when items are placed and removed and when it is time to do the laundry. A particularly ripe area for inventory control is the medicine cabinet. Placing small micro-cameras in the sides and doors would make it possible to identify different medicines and health products and even to obtain key information from bar-codes or QR codes. This information could then be used to maintain an inventory to observe when medicines are taken and when they pass their expiration date. It can also be used to maintain a log of when medicines are taken and replaced as an aid to persons with memory problems.

Autonomic maintenance for smart homes should also include detection and removal of waste and trash. Human waste is currently handled quite effectively by toilets, showers and wash basins, without need for information technologies. However removal of solid waste (packaging, used articles, etc.), and organic waste from meal preparation remains a manual task. Trashcans can be augmented with sensors to aid in sorting for recycling.

Cleaning robots for floors already exist as stand alone products operating on preprogrammed timers. Such devices could be operated as peripheral cleaning appliances to be awoken and directed by the smart home as needed. Cleaning of eating and living areas, floors and furniture is more challenging and will likely require substantial robotics engineering. Similarly, automatic cleaning of bathrooms, toilets, sinks and kitchen surfaces are likely to be higher payoff but at a substantially larger investment in engineering effort. On the other hand, as discussed above, available technology can be used to observe such surfaces and note when they have been cleaned and detect when they need to be cleaned. This can be of strong interest for hospitals, hotels and assisted living facilities. These examples can be seen as "low-hanging fruit" that have become feasible at reasonable price using recent advances in machine learning, sensing, computer vision and robotics.

The analogy of smart home as an inside-out autonomous robot can only take us so far in understanding the range of possibilities for innovation. Beyond autonomic control for homeostasis, it is increasingly feasible to endow a home with a form of intelligence. Robots are considered to be intelligent if they are autonomous, embodied and exhibit situated behavior [12]. An embodied robot must be able to act on the world. For a smart home, this can be as simple as control of HVAC equipment, or as complex as controlling internal robotic devices cleaning and waste removal. Situated behavior is behavior that is appropriate to the goals and environment of the robot. For a smart home this would mean behaving in a manner that complies with the expectations and requirements of inhabitants. In addition to the simple autonomic services described above, intelligence requires that services understand inhabitants and behave in a socially appropriate manner. To better understand how smart systems can behave in an appropriate "situated" manner, we propose to consider the nature of the interaction that services can have with inhabitants.

4 Intelligent Services for the Smart Home

In human societies, powerful people surround themselves with servants. Servants perform activities that provide value, such as cooking, cleaning, logistics and security. All of these activities depend on the visual, manual and cognitive abilities of the servant. For the most part, such abilities have remained beyond the state of the art in robotics and intelligent systems. However, this is rapidly changing with continued advances in the technologies of machine perception, machine learning, actuators, materials, and spoken language interaction. A popular consensus is that these technologies will eventually lead to intelligent humanoid robots that can take on the role of servants. However, this may not be the most appropriate or the most effective manner to bring intelligent services to the home.

Rather than trying to replace human servants with humanoid robots, it may be more appropriate to consider the kinds of services that can be provided by a smart home. In this section, we propose four categories of smart home services: tools, housekeepers, advisors, and media. These categories are defined by the way in which they interact with inhabitants [13]. For each category, we propose a definition and then describe several examples of possible services, most of which can be attained with existing technology. We conclude with a discussion of relative potential for penetration. In the following section, we will discuss qualities that can affect the acceptability and rate of adoption of smart home services.

4.1 Tool Services

A tool is a device or implement used to achieve a goal. Historically, human tools were mechanical artifacts, such as kettle that could be placed on a fire to heat water. The arrival of electricity made it possible to augment tools with energy. The kettle could now be equipped with its own heating element, obviating the need for a fire. Replacing analog controllers with digital controls makes it possible to dramatically increase the range of functions, and the precision of the tool. The kettle can now be equipped with a digital thermometer and offers preprogrammed modes to heat water for the exact temperature required for coffee, tea or instant soup. Augmenting tools with abilities to perceive, learn, communicate and interact offers even greater range of functions, but poses particularly difficult challenges. Allowing the kettle to adapt to each inhabitants' preference for the temperature of tea raises a real danger of rendering the kettle unusable.

The kitchen can be a rich domain for smart objects. For example, the mechanical can opener is a classic tool. Adding electricity gives us an electrical can opener, reducing the need for human force. Adding sensors and digital controls makes it possible to create a digital can opener that can adapt its shape and force to automatically penetrate and open cans of any size and material. Adding computing and sensors to recognize the can (peaches or pears), gives us a smart can opener that keeps track of what was opened and when.

Interconnected smart objects can be orchestrated to create a variety of new services for which there are no current analogs. For example, instrumenting cabinets and storage closets makes it possible to create a memory prosthesis tool that we refer to as "Where is my stuff?". Augmenting a refrigerator with recognition contents would enable a service that adjusts temperature to contents for optimum freshness.

The nature of "tool-ness" is not in the function, but in the way in which the device is used by inhabitants. Tools should perform a specific task or function as robustly as possible under the control of an inhabitant. They should be reliable and invariant. Any intelligence should be used to enable the service to provide exactly the expected behavior under changes in operating conditions. The user interface and interaction with users should be perfectly predictable.

4.2 Housekeeping Services

Housekeeping services perform the chores involved in running a household, such as cleaning, cooking, home maintenance, shopping, and laundry. As with a human servant, housekeeping services should fade into the background and perform their task unobtrusively as a form of calm technology as proposed by Weiser [14]. Services for evacuation of waste, cleaning, management of consumable supplies and maintaining integrity of home and its appliances, discussed above, are examples of Housekeeping services.

Housekeeping Services automate existing processes and thus can be seen as similar to time-saving appliances. While they can result in some improvements in quality of life, inhabitants may be less willing to invest time and money in their adoption. Penetration rates are likely to remain modest for reasons discussed above in section 3.2.

As with human servants, housekeeping services operate with knowledge of the most intimate details of each inhabitants' activities. Placing the information for such services on a cloud computer potentially reveals such details to companies and government services that happen to have the cryptographic keys. For this reason, privacy and trustworthiness are essential for Housekeeping Services.

4.3 Advisor Services

Advisor services observe the inhabitants and their activities in order to propose information on possible courses of actions. Advisors are analogs to experts such as doctors, culinary chefs or personal coaches for health, grooming or fashion. Advisors should be completely obedient and non-disruptive. They should not take initiatives or actions that cannot be overridden or controlled by the user. They should not create an unwanted distraction (nagging). Rather than saving time, advisors serve to improve the quality and effectiveness of inhabitants' activities.

An obvious example is a service that advises inhabitants on how to make more effective use of energy and the smart grid. Such a service would observe inhabitants' daily routines and patterns of energy consumption in order to suggest ways in which the inhabitant could reduce energy consumption with little or no change to comfort or personal habits. This information could be combined with information from the smart grid on current and expected pricing to advise users on how to minimize their electricity bill.

More generally, Advisor Services can be constructed to inform inhabitants on how to reduce their overall cost of living. A kitchen advisor could provide suggestions for meals based on current contents and expiration dates of food in the pantry and refrigerator. A cooking advisor would observe inhabitants' actions in preparing meals, and offer suggestions on how to improve taste or nutritional quality, or reduce cost of meals. An entertainment advisor could draw information from the Internet on television and cable schedules, as well as cultural events and movies. This could be combined with information about inhabitants' tastes and preferences to suggest possible leisure activities. A security advisor could be constructed to observe an inhabitant's routines to warn of potential dangers to person or property.

A number of research laboratories and companies are currently working on advisor services for sports training, weight loss and active healthy aging. Such services can be augmented with information from wearable activity sensors and models of the "quantified self" to provide advice and encouragement concerning physical activity and meals. Services can be devised to guide recovering patients about prescribed and proscribed activities during recovery from surgery. We have recently worked on an emotional coach that can monitor emotions of seniors and act to stimulate affection to prevent depression.

An important, unsolved, challenge for advisor services is how to enable such services to communicate in an unobtrusive manner, respecting the user's attention. Nanny bots that nag do not provide an improvement to quality of life, and are not likely to be adopted by anyone who controls their own habitat. Weiser's notion of a Calm Technology is once again relevant.

An even more critical issue is the problem of legal responsibility. Who is responsible when an advisor service gives incorrect or harmful advice? Can consumers be protected from services that give advice that surreptitiously leads to undue profit by companies? The potential for abuse is enormous.

4.4 Media Services

Media services provide extensions to perception and experience, including entertainment, communications, and non-obtrusive peripheral display of information. Music and art in the home are historical forms of media. Radio, television, and the telephone are examples of media made possible by the arrival of home electricity. The world-wide web is an extremely rich form of media made possible by the Internet. Ambient intelligence will enable an explosion of new media services with no obvious analogs to the past.

The arrival of inexpensive interactive displays will make it possible to augment every surface with interactive access to information via the web. It is already possible to embed interactive displays in glass[1]. Low cost wall-paper that includes color display and tactile interaction should soon be possible using technologies such as

[1] Corning - A day made of Glass: https://www.youtube.com/watch?v=jzLYh3j6xn8

OLED or Graphene. When every surface is an interactive display, avoiding sensory overload of inhabitants may become a real challenge. Such a technology would enable the home to become a form of augmented reality blending the physical and virtual in a seamless experience. This can make possible, for example, a sense of presence with remote family members and loved ones. It can offer ubiquitous access to social media such as Twitter and Facebook, as well as immediate access to internet search. Video communications and entertainment can follow the inhabitant anywhere in the house.

Tangible and peripheral displays [15, 16] are another example of media made possible by ambient intelligence. Ordinary objects can be augmented with motion, light and sound to provide information about weather, traffic, or the activity of close family members. Internet-enabled lamps, such as the Philips Hue have been used to unobtrusively display information such as the cost of electricity [17] or energy consumption [18]. Similar services have been proposed to announce imminent arrival of family members or changes in weather conditions.

Episodic memory is a form of media service for which there is currently no analog. Such memory can take many forms. For example, engineers at INRIA Grenoble recently constructed a “refrigerator time machine” that uses micro-cameras to keep a visual record of items that are placed and removed from a refrigerator, combined with an interactive tablet interface that allowed an inhabitant to browse the visual history of the interior. This could be combined with visual recognition to identify and record individual items as they are placed or removed. The identity of the inhabitant that operated the refrigerator door could be used to record who what and when for every item. Similar systems could be constructed for cabinets and storage areas, making it possible to maintain a dynamic inventory.

Episodic memory can also be used to augment work surfaces. Low cost RGBD sensors can be used to observe ordinary objects as well as the human hands that manipulate them. Techniques currently exist to geometrically model the configuration of the hand and to detect common actions such as pick, place, turn, pour, stir, etc. [19, 29]. Recent progress in computer vision and machine learning make it possible to robustly detect and recognize ordinary objects from arbitrary view points and lighting conditions [21, 22]. Combining these techniques makes it possible to create episodic memories for kitchen work surfaces, dining tables, and bathroom surfaces. Visual recordings can be segmented and organized with event detection to provide a searchable record of actions and activities that occur at surface. These can be made available to inhabitants through interactive displays. Such tools provide a promising new approach to helping seniors avoid over medication, monitoring eating habits and offering interactive cooking advice.

4.5 Categories of Service are Based on Interaction

The proposed categories of smart services are defined by the way they interact with inhabitants rather than by the domain in which they operate. For example, episodic memory, discussed in the previous section, can be used to construct a tool (“Where is my stuff”), an advisor (“How can I make a better cake?”) or a media (“display of recent events”). These categories do not provide an unambiguous partition of the space of possible services. Indeed, in some cases, some services can be seen as belonging to more than one category, depending on which facet of the service is examined and the goal for which it used. It is likely that other categories can be defined.

5 Qualities and Show Stoppers for Smart Home Services

In this final section, we discuss required qualities and possible “show-stoppers” for smart home services. A quality defines the behavior of a system or service, and can be key in determining acceptability and rate of adoption. Qualities should ideally be defined as measurable attributes. For example, in the domain of Service Oriented Software, important qualities include Availability, Assurance, Usability and Adaptability. Each of these can be defined by measurable quantities.

Qualities are often defined as hierarchies, with general categories of quality made up with more detailed sub-categories. For example, Boehm defined a hierarchical model for software quality in which the highest-level qualities are Utility, Maintainability, and Portability [23]. Each of these is composed of a number of more detailed qualities. Show-stoppers are critical qualities with the potential to impede or even prevent adoption of technology. We begin with discussion of qualities that can affect the rate of adoption and the degree of satisfaction of inhabitants. We continue with examples of show-stoppers that could impede or prevent the emergence of smart home services if not properly addressed.

5.1 Controllability

Quality of life (QoL) is the general well-being of individuals and societies. In healthcare, a common metric of Quality of Life is the degree to which a person enjoys the opportunities of their life to achieve Being, Belonging, and Becoming. Control of ones’ personal habitat is an important component of general well being, and will be an important factor in the rate with which individuals will invest time and money in smart home services.

A Smart Home can be seen as a micro-cloud composed of specialized CPUs, data storage units, sensors, actuators and interaction devices. The result is a complex heterogeneous ecosystem with a very large space of possible services. Mastering this complex ecosystem is a difficult challenge, especially if each home harbors a unique collection of devices.

In [24] the authors consider two approaches to providing smart home services in such a space: Smart Home Apps (Apps) versus End User Development (EUD). The Apps approach is attractive because it frees users from having to think about what they want. Users can opportunistically retrieve Apps from an App Store, even when they are looking for something else. While this model has proven popular for smart phones, the smart home differs from a smart phone in many critical aspects. The technical components of a smartphone are well defined whereas those of Smart

Homes are diverse and unpredictable. Apps for Smart Homes must accommodate a great variety of underlying hardware. Smart phones tend to be used by one task at a time, while scenarios for Smart Homes envision a large number of services running in parallel. Finally, the smartphone is the intimate property of one owner, while a home, in general, is a shared spaces inhabited by a family or small group.

The End User Development (EUD) approach allows inhabitants to craft the behavior of their homes in accordance with their tastes and needs. This approach is well suited to the distributed collection of heterogeneous devices likely to populate a smart home, and allows users to opportunistically create new services and new uses for existing services. EUD allows inhabitants to remain masters of their home and the services that it provides, thus deriving a sense of personal satisfaction, contributing to quality of life.

5.2 Reliability and Maintainability

Home services are critical services [25]. They must be reliable and maintainable. Failures must be graceful with built-in safeguards and backups so as not to threaten health or property. This would seem to be antagonistic with a requirement for controllability and End User Development, particularly given the heterogeneous nature of a smart home infrastructure. Thus, reliability and maintainability of end-user developed smart home services appears to be one of the key research challenges to the development of smart home technologies. So far, this research challenge has not been widely recognized.

5.3 Usability

Smart home services must also be usable [26]. The contextual nature of usability has recently been recognized by the International Organization for Standardization/International Electrotechnical Commission (ISO/IEC) 9126 standards developed in the software community with the overarching notion of "quality in use." Unfortunately, usability is viewed as only one independent contribution to quality in use. Thus, the temptation is high for engineers to assimilate usability with cosmetic qualities of the user-interface, forgetting that system latency, reliability, missing functions, and inappropriate sequencing of operations can have a strong impact on the system "use worthiness."

Use worthiness is central to Cockton's argument for the development of systems that have value in the real world [27, 28]. In value-centered approaches, software design starts with the explicit expression of an intentional creation of value for a selected set of target contexts of use. Intended value for target contexts are then translated into evaluation criteria. Evaluation criteria are not necessarily elicited from generic intrinsic features such as time for task completion, but are contextualized. They are monitored and measured in real usage to assess the achieved value. Achieving this for smart homes is a critical challenge.

5.4 Durability

Smart Home Technologies must be durable. They should have technological life cycles that are on the same temporal scale as the home. Programmed obsolescence is not an option. This quality can be particularly challenging during times of rapid technological evolution. It would encourage novel uses of mature technologies rather than adapting emerging technologies to existing uses.

Durability is yet another reason that closed proprietary standards are incompatible with smart home services, particularly when employed by startups and small enterprises with limited expected life spans. Long-term durability argues for open standards and open source software and hardware designs.

5.5 Security, Privacy and Trustworthiness.

The potential for abuse of smart home services by companies and governments constitutes the biggest danger for their development. Such services will operate with very intimate details of daily life that go beyond anything imagined by George Orwell in his novel 1984 [29]. Even without video or audio recording, smart home services can acquire detailed records of daily routines for eating, sleeping and bathing. Personal tastes in clothing, entertainment, food and social interaction would all become transparent. Once recorded, such information can potentially be eternal.

Personal information has value. Without legal restraints, it is very tempting for companies to base a business plan on the hidden value of customer information, particularly when it is "protected" overly complex "user agreements" written in legal jargon. Many consumers are likely to be seduced by offers of inexpensive or free smart objects and services whose true cost is paid with the personal information that is harvested and exploited by companies. It is difficult to overstate the potential for abuse if current practices concerning collection of personal information on the web are allowed to proliferate into smart home technologies.

In most Western countries, personal information is protected by legal guarantees. However, recent history has shown that such guarantees are easily ignored in times of crisis. Government powers for surveillance of citizens imposed for specific needs in a crisis are easily made permanent and gradually adopted for everyday use by law enforcement. Certain governments have declared that any information that transits the Internet can be collected and used for surveillance. This should raise warnings for anyone considering using smart home services based on cloud computing. Obviously, smart devices and smart home services must be secure by design. However, even the best cryptographic coding can be undone by careless behavior, misleading user agreements or brute-force computing.

Legal restraints on corporate and governmental collection and use of personal data are important to the future of the smart home. However, even if companies and government bodies agree to obey legal restraints, how can inhabitants trust smart home services? A few cases of abuse can easily blossom into widespread suspicion and distrust. Clear rules and aggressive legal protection of privacy are essential.

6 Concluding Remarks

Throughout history, humans have relied on a personal habitat for protection and shelter from the elements. As human technology has evolved, the home has increasingly become a source of services. Mastery of fire enabled the home to provide heat, light and preparation of food. Bronze and iron enabled new forms of lamps and stoves. Technologies for candle wax and kerosene provided increasingly cleaner light. Electricity triggered a revolutionary expansion of services as ordinary objects were augmented with electrical power, and new media such as telephones and radio were invented.

Information and communications technologies are poised to trigger a new revolution in services provided by the home. In this paper, we examined this revolution in the larger historical context. We have proposed an ecological view in which the home is seen as a personal habitat that provides services to inhabitants. We have examined the smart home using the metaphor of an inside-out autonomous robot providing autonomic services that maintain stability in the internal environment. We have defined four categories of smart home services: Tools, Housekeepers, Advisors and Media and given examples of possible services in each category. We have reviewed qualities that can be used to describe and compare smart home services, and discussed potential show stoppers that could prevent the emergence of the smart home.

Two competing approaches emerge for the development of smart home technologies. In one view, users are passive consumers who willingly trade their data in exchange for the convenience of smart services. This approach is compelling both because it frees the user from the challenge of configuring and maintaining systems, and because it makes it possible for established companies to apply modern machine learning and big data analysis to construct smart home systems. The challenge to companies is to provide services that are so compelling and easy to use that end-users surrender control of both system behavior and personal data. The danger is that end-users will become prisoners of closed ecosystems of smart home services subject to the dictates of the large companies.

An alternative is that end-users retains local control of data and services, at the cost of investing the effort required to configure and manage smart home services in a changing landscape of devices and network protocols. The challenge to the scientific community is to provide robust tools and systems that are usable by ordinary people. Crowd source development offers an enticing tool for this approach. Our experience shows that the enabling technologies for EUD are now sufficiently mature as to support an open source community of geeks and hobbyists that can unleash the power of crowd sourcing for developing new systems and services. The challenge to this community is to make the technology usable by the masses without sacrificing control of smart home services or personal data.

Security, privacy and trustworthiness are essential to acceptance and acceptability of the smart home. While these are measurable technical qualities, ultimately their assurance requires ethical and legal safeguards. If companies and governments are allowed to freely exploit this new technology to track and monitor inhabitants, as they already have with the worldwide web, then smart home technologies will become a prison that goes beyond Orwell's vision of 1984. It is our responsibility to assure that this does not happen.

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